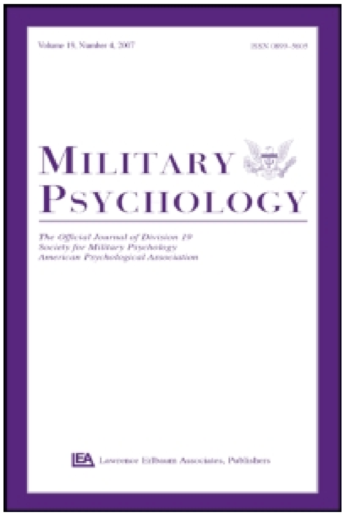

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Cerebral Hemodynamics and Vigilance Performance

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Cerebral Hemodynamics and Vigilance Performance

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Five studies are described using transcranial Doppler sonography (TCD) and near-infrared spectroscopy (NIRS) to examine brain systems in vigilance. The results indicate that the vigilance decrement, the temporal decline that typifies vigilance performance, is paralleled by a decline in cerebral blood flow velocity as indexed by TCD. In addition, both measures showed greater activity in the right than in the left cerebral hemisphere in response to a variety of psychophysical challenges, indicating a right hemispheric system in control of vigilance performance. The TCD measure was also found to be potentially useful in selecting observers for vigilance assignments.

INTRODUCTION TO VIGILANCE

The study of vigilance, or sustained attention, concerns the ability of observers to detect transient and infrequent signals over prolonged periods of time. That aspect of human performance is of considerable concern to human factors/ergonomic specialists because of the critical role that operator vigilance plays in many automated human–machine systems, including military surveillance, air traffic control, cockpit monitoring and airport baggage inspection, industrial process and quality control, and medical functions such as cytological screening and the inspection of anesthesia

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gauges during surgery (Warm & Dember, 1998; Warm, Parasuraman, & Matthews, 2008). Failure of signal detection in these situations can have disastrous consequences for system productivity and for public safety and health. Thus, it is important to understand the psychophysical and neurophysiological factors that control vigilance performance. Toward that end, we shall describe a series of five experiments that we and our colleagues have recently completed using transcranial Doppler sonography (TCD) and near-infrared spectroscopy (NIRS) to examine brain systems in vigilance under a variety of psychophysical challenges. Additional descriptions of this work can be found in Warm and Parasuraman (2007) and Warm et al. (2008).

Consistent with the view first proposed by Sir Charles Sherrington in 1890 (Roy & Sherrington, 1890), a considerable amount of current research on brain imaging indicates that there is a close tie between cerebral blood flow and neural activity in the performance of mental tasks (Raichle, 1998; Risberg, 1986). Along that line, a resource model of sustained attention in which changes in blood flow velocity and oxygenation are considered to reflect the availability and utilization of information processing assets needed to cope with the vigilance task served as the theoretical basis for our work. The results of our studies indicate that (a) the decline in the accuracy of signal detections over time that typifies vigilance performance, the vigilance decrement, or the decrement function (see Figure 1) is accompanied by a parallel decline in cerebral blood flow velocity, (b) the effects of different psychophysical manipulations are also paralleled by changes in blood flow velocity, and (c) these effects are lateralized to the right cerebral hemisphere, indicating the operation of a right hemispheric system in the functional control of vigilance performance.

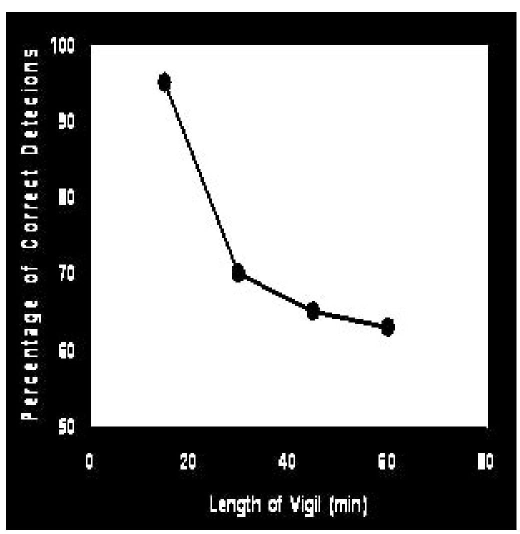


FIGURE 1 The vigilance decrement.

BRAIN SYSTEMS AND VIGILANCE

In recent years, brain imaging studies utilizing positron emission topography (PET) and functional magnetic resonance (fMRI) techniques have been successful in demonstrating that changes in cerebral blood flow and glucose metabolism are involved in the performance of sustained attention or vigilance tasks (Parasuraman, Warm, & See, 1998) These studies have also identified several brain regions that are active in such tasks. Included are the frontal cortex, the cingulate gyrus, the left intralaminar region of the thalamus, the midbrain tegmentum, the locus ceruleus, and the reticular formation in the brain stem. These areas are displayed in Figure 2.

Although these studies have identified brain regions involved in vigilance, a careful review by Parasuraman et al. (1998) has pointed out some major limitations of this research. With the exception of PET studies by Paus et al. (1997) and by Coull, Frackowiak, and Frith (1998), the brain imaging studies have neglected to link the systems they have identified to performance efficiency, perhaps because of the high cost associated with using PET and fMRI during the prolonged running times characteristic of vigilance research. Thus, as Parasuraman et al. (1998) have noted, the functional role of the brain systems identified in the imaging studies remains largely unknown. Gazzaniga, Ivry, and Mangun (2002) have also emphasized the necessity of linking imaging studies to performance for an understanding of cognitive neuroscience, and Goldstein (2001) has highlighted the importance of tying psychophysical discriminations to physiological measures that he characterizes as *the linkage problem*.

Other difficulties with the PET and fMRI procedures are that they feature restrictive environments in which observers need to remain almost motionless throughout the scanning procedure so that the quality of the brain images is not compromised, and fMRI acquisition is accompanied by loud noise. Observers in vigilance experiments rarely remain motionless, however. Instead, research has shown that they tend to fidget during the performance of a vigilance task, with the amount of motor activity increasing with time on task, as illustrated in Figure 3, taken from a study by Galinsky, Rosa, Warm, and Dember (1993).

Moreover, noise is one of several environmental variables that can degrade vigilance performance. For example, Figure 4, from an experiment by Becker, Warm, Dember, and Hancock (1995), shows that noise can lower perceptual sensitivity in a vigilance task, interfere with the ability of observers to profit from knowledge of results, and elevate perceived mental workload. In this study, background noise came from a jet engine as the plane it was powering moved across the observer's acoustic field. Workload was measured by the NASA Task Load index, a standard measure of perceived mental workload (Wickens & Hollands, 2000).

Accordingly, the conditions required for the effective use of the PET and fMRI techniques may not provide a suitable environment for linking changes in brain physiology with vigilance performance over a prolonged period of time. What is needed is an imaging technique that will avoid these shortcomings to help bridge

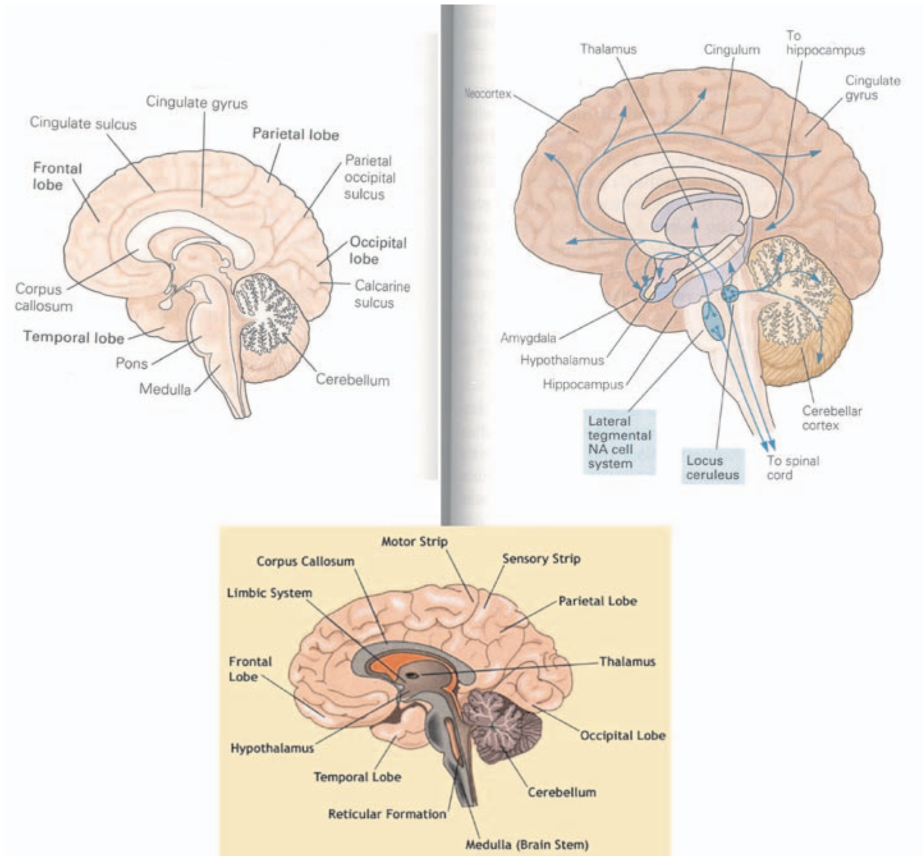


FIGURE 2 Brain regions involved in the performance of vigilance tasks.

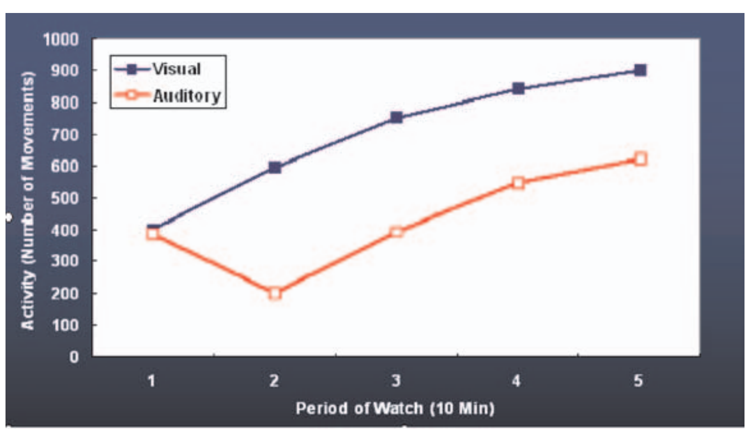
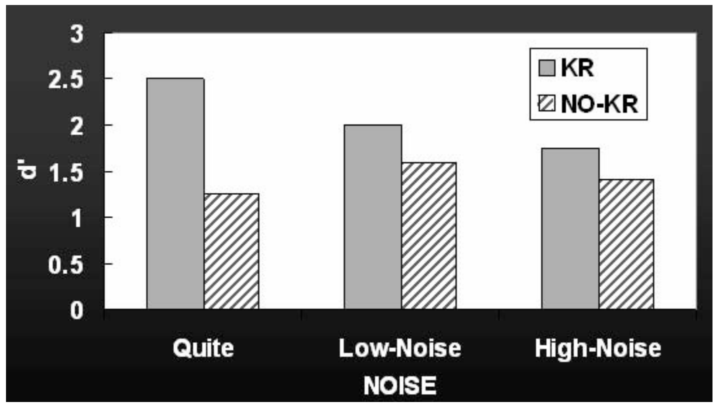


FIGURE 3 Activity level as a function of periods of watch in the visual and auditory modalities. After Galinsky et al. (1993).



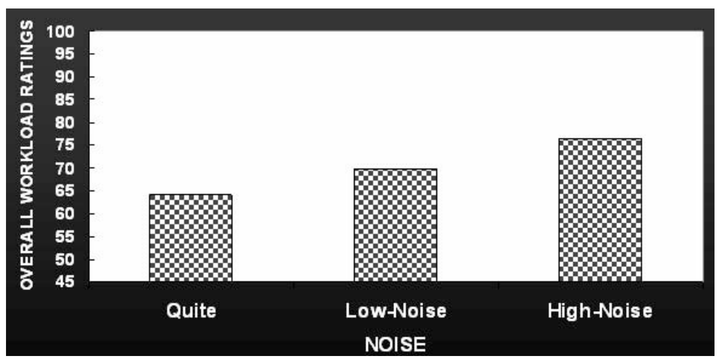


FIGURE 4 Top panel: Perceptual sensitivity in combinations of background noise and knowledge of results. Bottom panel: Perceived mental workload in quiet and two levels of background noise. After Becker et al. (1995).

the gap in our understanding of performance and brain systems in vigilance. Accordingly we turned to TCD as an alternative imaging technique.

THE TCD ALTERNATIVE

TCD is a noninvasive neuroimaging technique that employs ultrasound signals to monitor cerebral blood flow velocity or hemovelocity in the mainstem intracranial arteries and the middle, anterior, and posterior arteries (shown in Figure 5).

These arteries are readily isonated through a cranial transtemporal window and exhibit discernible measurement characteristics that facilitate their identification (Aaslid, 1986). As illustrated in Figure 6, the TCD technique uses a small 2-MHz pulsed Doppler transducer to gauge arterial blood flow.

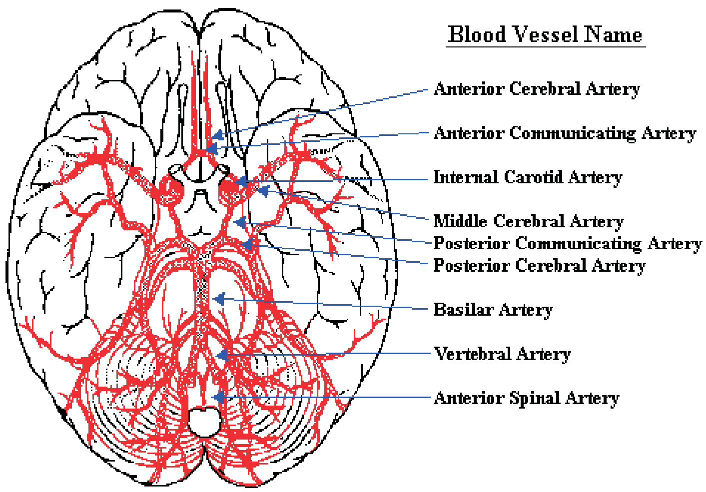


FIGURE 5 The anterior, middle, and posterior cerebral arteries.

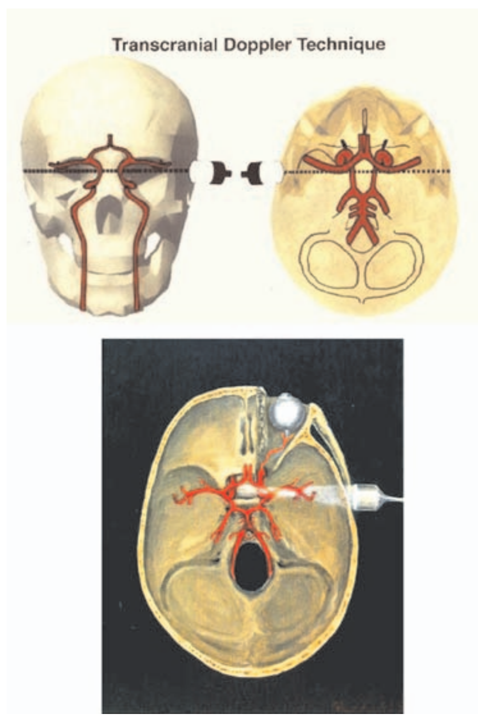


FIGURE 6 The transcranial Doppler technique.

The transducer is placed just above the zygomatic arch along the temporal bone, a part of the skull that is functionally transparent to ultrasound. The depth of the pulse is adjusted until the intracranial artery (e.g., the middle cerebral artery) is isonated. TCD measures the difference in frequency between the outgoing and reflected energy as it strikes moving erythrocytes. The low weight and small size of the transducer and the ability to embed it conveniently in a headband permit real-time measurement of cerebral blood flow velocity in both cerebral hemispheres while not limiting or becoming hampered by body motion. Therefore, TCD enables inexpensive, continuous, and prolonged monitoring of cerebral blood flow activity in the right and left cerebral hemispheres concurrent with task performance. Blood flow velocities, measured in centimeters per second, are typically highest in the middle cerebral artery (MCA), and the MCA carries about 80% of the blood flow within each cerebral hemisphere (Toole, 1984). Consequently, we measured blood flow from left and right hemisphere branches of the MCA in our experiments using a TC2-64B TCD unit manufactured by Nicolet/EME (Madison, Wisconsin).

When a particular area of the brain becomes metabolically active, as in the performance of mental tasks, byproducts of this activity, such as carbon dioxide (CO_2), increase. This increase in CO_2 leads to a dilation of blood vessels serving that area, which in turn results in increased blood flow to that region (Aaslid, 1986; Hellige, 1993). Consequently, TSD offers the possibility of measuring changes in metabolic activity during task performance. The use of TCD in brain imaging performance applications is limited, in part, by its low spatial resolution: TCD can supply gross hemispheric data, but it does not provide information about changes in specific brain loci, as is the case with PET and fMRI. Nevertheless, TCD offers good temporal resolution (Aaslid, 1986), and compared to PET and fMRI, it can track rapid changes in blood flow dynamics that can be followed in real time under less restrictive and invasive conditions.

In the past, TCD was used primarily in medicine for neurological diagnosis and for detecting the presence of intracranial vascular dysfunction (Babikan & Wechsler, 1999). Recent studies have indicated, however, that blood flow velocity in the MCA can be influenced by a variety of tasks such as stimulus detection and anticipation, reading aloud, listening to music, associating words, remembering a set of letters, solving mathematical problems, working with a complex performance battery, and making ethical decisions. In general, these cognitive activities accelerate blood flow velocity over resting baseline, and the TCD measured changes are linked to the cognitive demand imposed by the tasks (Tripp & Warm, 2007). For all of these reasons, we thought the TCD technique might be ideally suited as a tool for meeting the need identified by Parasuraman et al. (1998) to relate brain imaging in vigilance to performance efficiency.

THE SIMULTANEOUS/SUCCESSIVE TASK EXPERIMENT

The initial effort to use TCD in this way (Mayleben et al., 1998) was guided by a resource utilization model of vigilance proposed by Parasuraman and Davies (Davies & Parasuraman, 1982; Parasuraman & Davies, 1977) and tested intensively in our lab (Warm & Dember, 1998). According to that model, a limited-capacity information processing system allocates resources to cope with situations that confront it. The vigilance decrement reflects the depletion of information processing resources or reservoirs of energy that cannot be replenished in the time available. Changes in blood flow might reflect the availability and utilization of the information processing assets needed to cope with a vigilance task. Hence, Mayleben et al. (1998) hypothesized that the vigilance decrement should be accompanied by a decline in cerebral hemovelocity and that the absolute level of blood flow should vary directly with task demands.

To explore these possibilities, observers were asked to perform either a successive- or simultaneous-type vigilance task during a 30-min vigil. Successive tasks are absolute judgment tasks in which signals and nonsignals are differentiated by comparing current input against a standard held in working memory. In contrast, simultaneous tasks are comparative judgment tasks in which all the information needed to distinguish signals from nonsignals is present in the stimuli themselves and recent memory for the signal feature is not required (Parasuraman & Davies, 1977). Due to their memory imperative, Parasuraman and Davies argued that successive tasks are more capacity demanding than simultaneous tasks, a view supported by a wide variety of studies from our laboratory showing that simultaneous tasks are more resistant than successive tasks to the negative impact of psychophysical challenges that degrade vigilance performance by draining information processing resources (Warm & Dember, 1998). The specific displays used by the Mayleben team required discriminations of line length, as illustrated in Figure 7.

Critical signals for detection in the simultaneous task were cases in which one of the lines was 2 m taller than the other. In the successive task, critical signals were cases in which both lines were 3 mm taller than usual. Pilot work ensured that the tasks were equated for difficulty under alerted conditions.

In this and all subsequent studies, the MCA in both the right and left cerebral hemispheres was monitored at depths of 55 mm; the TCD unit calculated a hemovelocity average (cm/s) approximately every 4 s, and scores for individual observers were calculated as a proportion of the last 60 s of their 5-min resting baseline. In addition, all observers were right-handed.

The vigilance decrement, as reflected in a decline in signal detections over time, obtained by Mayleben et al. (1998), is shown in Figure 8. As expected, the decrement was accompanied by a parallel decline in cerebral hemovelocity (see Figure 9).

Also consistent with expectations from a resource model, the absolute level of blood flow was significantly higher for observers who performed the successive

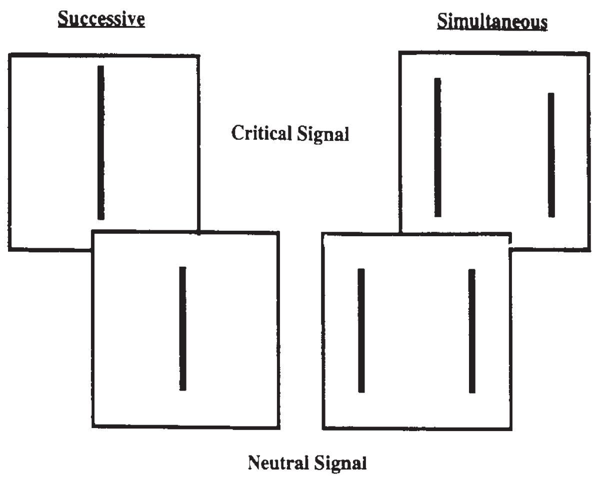


FIGURE 7 The successive- and simultaneous-type vigilance displays employed in the Mayleben et al. study (1998).

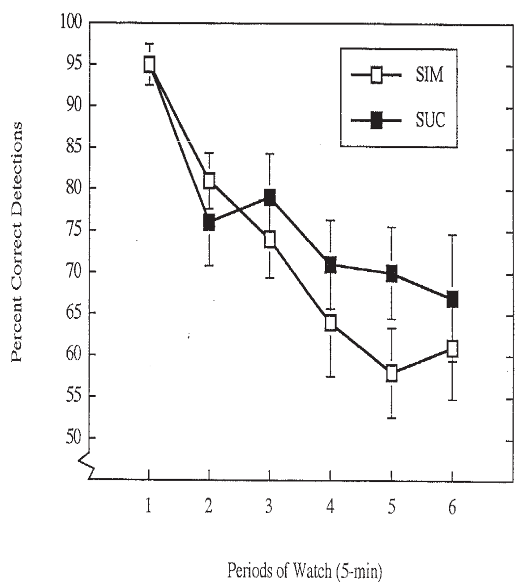


FIGURE 8 Mean percentage of correct detections as a function of periods of watch for the simultaneous (Sim) and successive (Suc) tasks. Error bars are standard errors. After Mayleben et al. (1998).

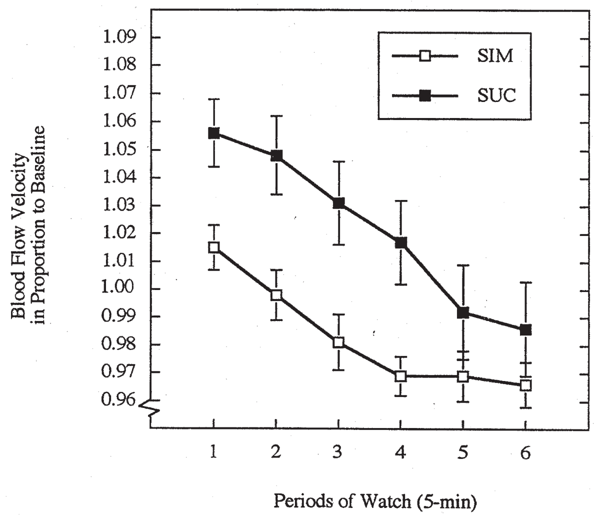


FIGURE 9 Mean cerebral blood flow velocity as a function of periods of watch for the simultaneous (SIM) and successive (SUC) tasks. Error bars are standard errors. After Mayleben et al. (1998).

task than for those who performed the simultaneous task (see Figure 10). An important finding in this study was that the blood flow effects were lateralized —hemovelocity was greater in the right than in the left hemisphere, principally in the performance of the memory-based successive task.

A result of this sort is consistent with earlier PET and psychophysical studies showing right-brain superiority in vigilance (Parasuraman et al., 1998) and with studies by Tulving, Kapur, Craik, Moscovitch, and Houle (1994) indicating that memory retrieval is primarily a right-brain function. Schnittger, Johannes, Arnavaz, and Munte (1997) have also reported the performance–blood flow velocity relation over time described in our study. However, a clear coupling of blood flow and performance could not be determined in their experiment because of the absence of a control for the possibility of spontaneous declines in blood flow velocity over time such as may result from systemic declines in arousal. Mayleben et al. (1998) employed such a control by exposing a group of observers to the dual-line display for 30 min in the absence of a work imperative. As shown in Figure 11, blood flow velocity remained stable over the testing period under such conditions.

A potential challenge to an interpretation of the present results along resource theory lines comes from the findings that blood flow velocity is sensitive to changes in blood pressure and cardiac output (Caplan et al., 1990) and that changes

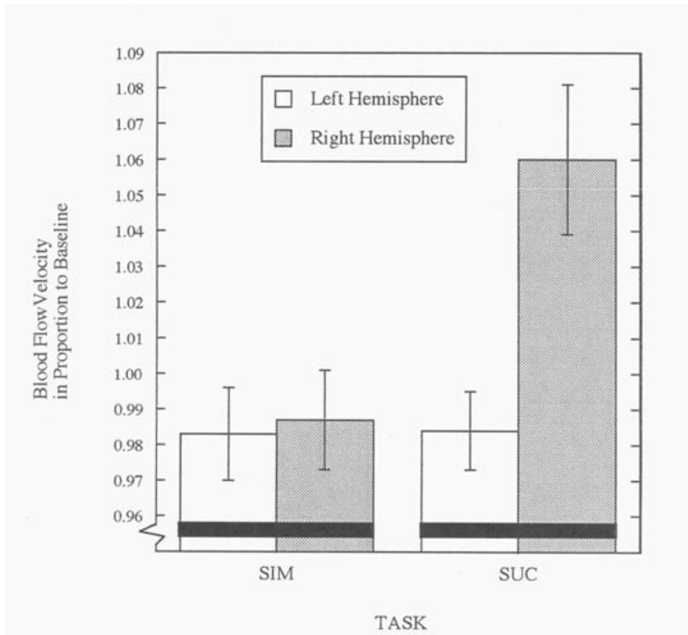


FIGURE 10 Mean overall blood flow velocity in the left and right hemispheres with the simultaneous (SIM) and successive (SUC) tasks. Error bars are standard errors. After Mayleben et al. (1998).

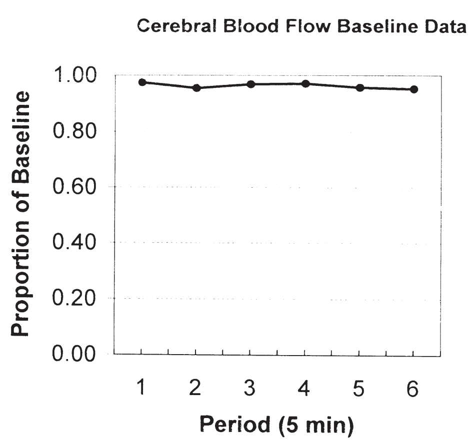


FIGURE 11 The timecourse of mean cerebral blood flow velocity scores in control observers who observed the vigilance display in the Mayleben et al. (1998) study without a work imperative.

in heart rate variability are correlated with vigilance performance (Parasuraman, 1984). Accordingly, one could argue that the performance/hemovelocity findings in this study do not reflect information processing per se but rather a gross change in systemic vascular activity that covaried with blood flow. The lateralization of the performance/hemovelocity findings challenges such a view, since gross changes in vascular activity are not likely to be hemisphere dependent.

THE CUEING EXPERIMENT

Signal detection in vigilance can be improved by providing observers with consistent and reliable cues to the imminent arrival of critical signals. As several experiments have shown, the principal consequence of such forewarning is the elimination of the vigilance decrement (Davies & Parasuraman, 1982; Warm & Jerison, 1984). An illustration of this effect comes from a study by Hitchcock, Dember, Warm, Moroney, and See (1999) using a simulated air traffic control display in which critical signals for detection were planes traveling on a collision course, as illustrated in Figure 12.

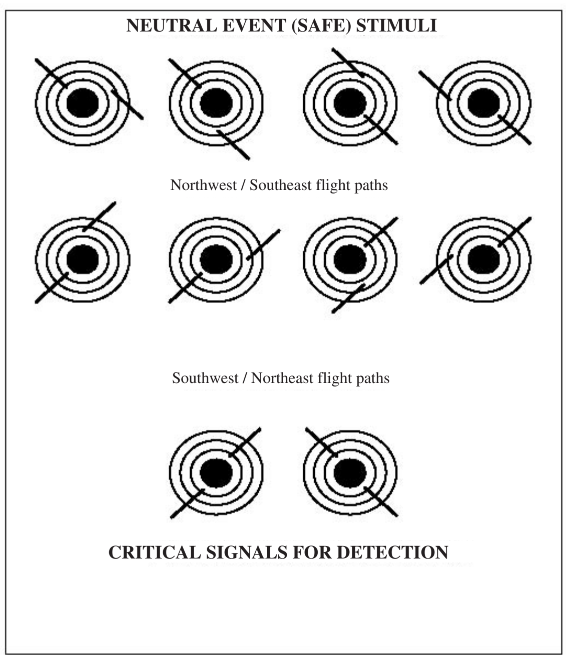


FIGURE 12 The simulated air traffic control display employed in the Hitchcock et al. (1999) study.

As illustrated in Figure 13, detection probability scores for cued observers remained stable as time on watch progressed, while they declined considerably over time for non-cued observers.

Hitchcock et al. (1999) linked the cueing effects to resource theory by arguing that cued monitors would need to observe the display only after having been prompted about the arrival of a signal and, therefore, could husband their information processing resources over time. In contrast, since non-cued observers were never certain as to when a critical signal might appear, they would have to process information on their displays continuously across the watch, thereby consuming more of their resources over time than cued observers.

Based upon that line of reasoning, Hitchcock et al. (2003) performed another experiment in which they anticipated that in the presence of perfectly reliable cueing, the temporal decline in blood flow would be attenuated in comparison to a non-cued condition and also in comparison to conditions in which cueing was less than perfectly reliable, since observers in such conditions would not be relieved of the need to attend continuously to the vigilance display. Finally, in view of the previous brain imaging and psychophysical findings indicating that vigilance performance is controlled by the right cerebral hemisphere, we also anticipated that the hemovelocity effects in this study would be predominantly right lateralized.

Observers monitored the simulated air traffic display described above for 40 min under conditions in which signal salience, determined by the Michaelson con-

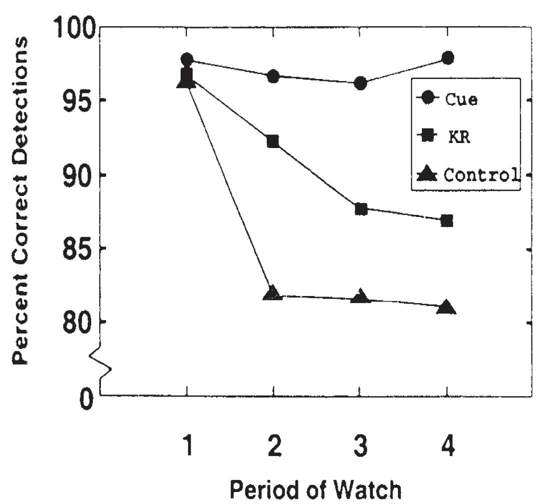


FIGURE 13 Mean percentages of correct detections as a function of time on task for the cue, knowledge of results (KR), and control groups. After Hitchcock et al. (1999).

trast ratio of the aircraft to their background, was high (98%, dark black planes on a light background) or low (2%, light gray planes on a light background). Signal salience was combined factorially with four levels of cue reliability (100% reliable, 80% reliable, 40% reliable, and a no-cue control). In all conditions the display was updated 30 times/min with a dwell time of 300 ms. Observers in the cueing groups were instructed that a critical signal would occur within one of the five display updates immediately following the verbal prompt "LOOK" provided through a digitized male voice. Observers in each of the cue groups were advised about the reliability of the cues they would receive. To control for accessory auditory stimulation, observers in the no-cue group received acknowledgement after each response in the form of the word "LOGGED" spoken in the same male voice.

As illustrated in Figure 14, the detection scores for the several cueing conditions were similar to each other during the early portion of the vigil and diverged by the end of the session. More specifically, performance efficiency remained stable in the 100% reliable cueing condition but declined over time in the remaining conditions, so that by the end of the vigil, performance efficiency was clearly best in the 100% group followed in order by the 80%, 40%, and no-cue groups.

The heomovelocity scores from the left hemisphere showed a significant decline over time but no effect for cueing with either high-salience or low-salience signals. A similar result was found for high-salience signals in the right hemi-

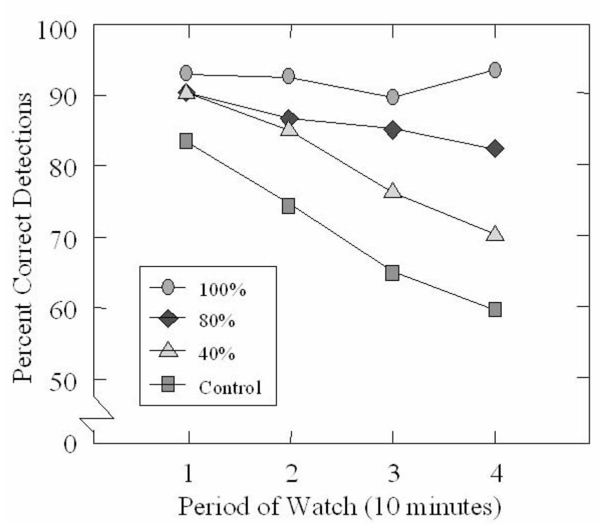


FIGURE 14 Mean percentage correct detections as a function of time on watch for four cue-reliability conditions. After Hitchcock et al. (2003).

sphere. Cueing effects emerged, however, in the hemovelocity scores for the right hemisphere with low-salience signals, as illustrated in Figure 15.

As was the case with detection probability, the hemovelocity scores for the several cueing conditions were similar to each other during the early portions of the vigil but showed differential rates of decline over time, so that by the end of the vigil, blood flow was clearly highest in the 100% group followed in order by the 80%, 40%, and no-cue groups.

In summary, the hemovelocity scores taken from the right hemisphere under low-salience almost exactly mirrored the effects of cuing on performance efficiency. The finding that this result was limited to low-salience signals is consistent with a study by Korol and Gold (1998) indicating that brain systems involving glucose metabolism need to be sufficiently challenged in order for measurable physiological changes to emerge in cognitive and attentional processing tasks. Restriction of the cue/time/salience hemovelocity findings to the right hemisphere is consistent with expectations about right hemisphere control of vigilance. As in the initial study, blood flow velocity remained stable over time in both hemispheres throughout the watch when observers were exposed to the simulated air traffic display without a work imperative. That result is shown in Figure 16.

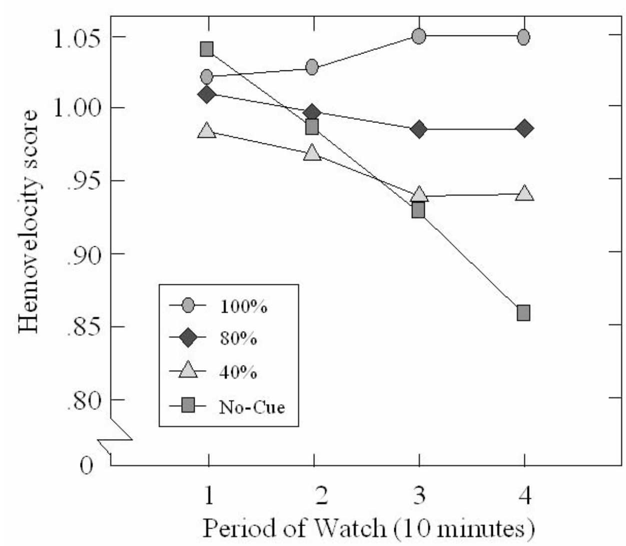


FIGURE 15 Mean cerebral hemovelocity scores as a function of periods of watch for four cue-reliability conditions. Data are from the right hemisphere with low signal salience. After Hitchcock et al. (2003).

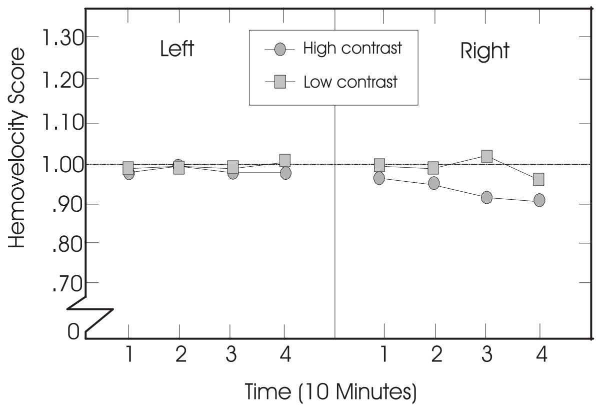


FIGURE 16 Mean cerebral blood flow velocity scores across time for control observers who observed the vigilance display in the Hitchcock et al. (2003) study without a work imperative. Data for the left and right cerebral hemispheres are presented in the left and right panels, respectively.

THE SENSORY FACTOR STUDY

At this point, all of our vigilance studies involving cerebral blood flow velocity were conducted in the visual modality. However, vigilance tasks can also be performed in the auditory modality and the sensory modality of signals is not a matter of indifference where vigilance is concerned. The overall level of performance in auditory tasks tends to be greater than that in visual tasks and the vigilance decrement is less pronounced in the auditory than in the visual modality (Warm & Jerison, 1984). In addition, several studies have reported that correlations between the two modalities are either low ($r < .30$) or nonsignificant (Warm & Jerison, 1984). Accordingly, in a recent study (Shaw et al., 2006) we sought to determine the degree to which the vigilance decrement is accompanied by a decline in cerebral blood flow velocity in comparable visual and auditory vigilance tasks.

There is theoretical justification for a study of this sort. One might conclude from the sensory differences we have described that sustained attention in audition and vision may be based upon different central properties, a possibility that would greatly complicate efforts to understand the mechanisms that underlie sustained attention. On the other hand, the presence in the literature of substantial intermodal correlations between auditory and visual vigilance tasks (*r*s ranging from .65 to .85) along with findings of successful intermodal transfer in training for vigilance and superior performance with redundant dual-mode audio/visual displays relative to single-mode auditory or visual displays led Warm & Jerison (1984) to affirm that while modality-specific factors are important, within limits, vigilant behavior is a common characteristic of the observer. Showing that the vigilance decrement in both sensory

modalities is accompanied by a similar decrement in cerebral blood flow velocity occurring in common cerebral arteries would support our position.

In a critical earlier study, Hatfield and Loeb (1968) raised an important methodological issue in regard to audio-visual comparisons in vigilance. They pointed out that disparities in the types of discriminations involved, the salience of the displays to be observed, and the difficulty of the discriminations to be made were not equated in previous studies of sensory differences in vigilance and could have contributed to the outcomes of those studies. Accordingly, since the perception of time correlates strongly in the auditory and visual modalities under alerted conditions (Loeb, Behar, & Warm, 1966), temporal discriminations were featured in our study, and efforts were made to specifically control for disparities in display salience and discrimination difficulty.

Observers participated in a continuous 40-min vigil divided into four 10-min periods of watch. Those monitoring the visual display viewed the repetitive presentation of a horizontally oriented white bar that appeared against a gray background on a video display terminal (VDT). Neutral events requiring no response from the observers were flashes lasting 247.5 ms. Observers monitoring the auditory display listened to 247.5-ms bursts of white noise presented binaurally via earphones inserted into the external auditory meatus of each ear. Critical signals in the visual case were brief 125-ms flashes of the light bar. In the auditory case, critical signals were brief 200-ms bursts. The disparity in duration changes used to specify auditory and visual signals was necessary to compensate for greater temporal acuity in the auditory mode under alerted conditions (Szalma et al., 2004). In all conditions observers equated the apparent loudness of the noise to the apparent brightness of the visual stimulus by means of a cross-modal matching procedure (Stevens, 1959). The displays were updated once every 2,000 ms and 10 critical signals were presented in each watch-keeping period. As in our previous studies, control observers were employed who looked at or listened to the visual or auditory displays for the same amount of time as the active observers but without a work imperative.

Performance efficiency was measured in terms of the percentages of correct detections and errors of commission or false alarms. As can be seen in Figure 17, both measures showed a significant linear decline over time on watch that was independent of the sensory modality of signals.

As illustrated in Figure 18, this effect was paralleled by a linear decline in cerebral blood flow velocity over time that was also independent of the sensory channel used for stimulus presentation. Blood flow velocity in both modalities was also greater in the right as compared to the left cerebral hemisphere.

As Figure 19 shows, blood flow velocity scores for passive control observers remained stable over time throughout the 40-min session for all combinations of sensory modality and cerebral hemisphere, indicating that the temporal declines in cerebral blood flow velocity were performance based.

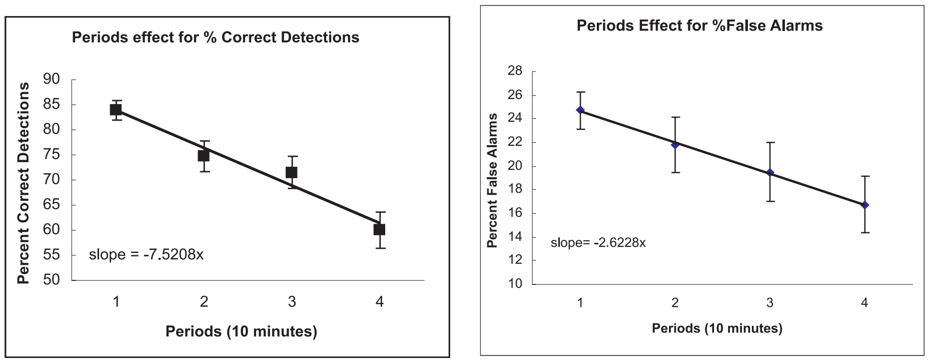


FIGURE 17 Mean percentages of correct detections and false alarms across sensory modalities as a function of periods of watch. Error bars are standard errors. After Shaw et al. (2006).

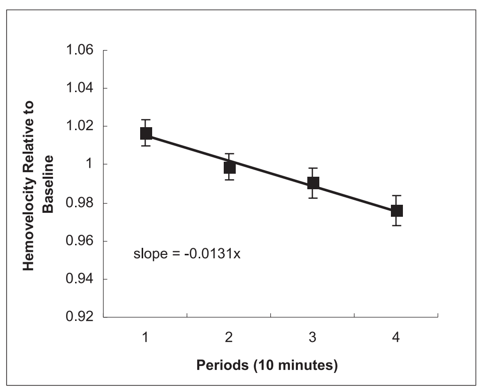


FIGURE 18 Mean cerebral blood flow velocity scores across sensory modalities as a function of periods of watch. Error bars are standard errors. After Shaw et al. (2006).

The results of this study clearly indicate that the temporal decline in cerebral blood flow velocity found in our earlier visual studies is not restricted to the visual modality; it occurs in the auditory modality as well. Similarly, the results indicate that the heightened level of blood flow velocity found in the right as compared to the left cerebral hemisphere in our earlier studies, a result pointing to a right hemispheric system in the functional control of vigilance performance, is also independent of the sensory modality used for stimulus delivery when hemovelocity is measured in an artery common to the two sensory channels. These findings are consistent with Warm and Jerison's (1984) argument that while stimulus-specific factors are important in vigilance, within limits, vigilant behavior is a common

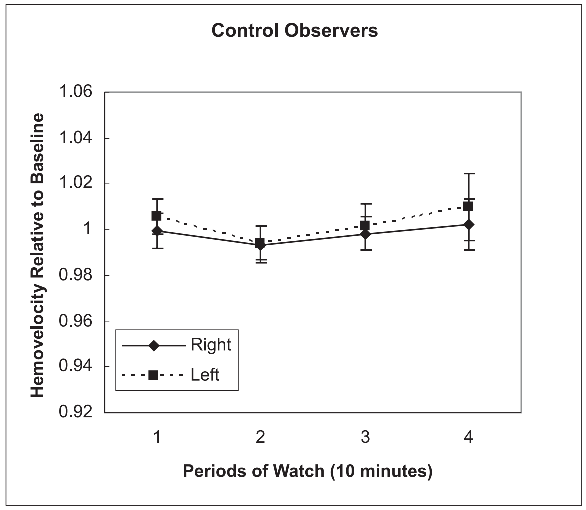


FIGURE 19 Mean cerebral blood flow velocity scores in the right and left cerebral hemispheres as a function of periods of watch for control observers who were exposed to the visual and auditory displays without a work imperative. Data are collapsed across sensory modalities. Error bars are standard errors. After Shaw et al. (2006).

characteristic of the observer. On a much broader level, our results are also consistent with findings in other areas that the brain engages in a synthesis of similar streams of information over different sensory channels (Calvert, Spence, & Stein, 2004; Poggel, Merabet, & Rizzo, 2007).

THE CEREBRAL OXYGENATION STUDY

To this point, our investigations of cerebral hemodynamics in sustained attention have made use of traditional vigilance tasks lasting 30 min or more. Because of their long duration, investigators have found it inconvenient to incorporate such tasks in test batteries or, as discussed previously, to link vigilance performance with brain imaging metrics such as PET and fMRI. Accordingly, Posner (1978) suggested that it should be possible to generate shorter-duration vigilance tasks that exhibit the same effects as the typical long-duration vigils. We have developed an abbreviated 12-min vigilance task composed of 6 consecutive 2-min periods of watch that appears to meet that standard (Temple et al., 2000). In performing that task, observers are asked to inspect the repetitive presentation on a VDT of light gray capital letters consisting of an “O,” a “D,” and a backwards “D.”

The letters are presented for only 40 ms at a rate of 57.5 events/min and are exposed against a visual mask consisting of unfilled circles on a white background (signal probability = 0.20/period of watch). Critical signals for detection are the appearance of the letter “O.” As in the case of long-duration vigils, performance in the abbreviated vigil has been found to vary inversely with signal salience varied via the Michaelson contrast ratio of the letters to their background and to be enhanced by a stimulant drug, caffeine (Temple et al., 2000; see Figure 20).

The demonstration that the cerebral hemodynamics associated with the abbreviated vigil duplicate those associated with long-duration vigil would provide additional evidence that the former represents a viable analog to the latter. Accordingly, Helton et al. (2007) spearheaded a study in our lab that examined the relationship between cerebral hemovelocity and performance on the abbreviated vigil.

In addition to the TCD measure employed in our long-duration studies, we made use of another nonrestrictive and relatively economic alternative to PET and fMRI—the assessment of cerebral blood oxygen saturation using NIRS (Gratton & Fabiani, 2007) via a Somanetics INVOS 4100 Cerebral Oximeter. The instrument’s sensors are embedded in a headband much like that used with the TCD procedure and recordings can be obtained simultaneously from both cerebral hemispheres.

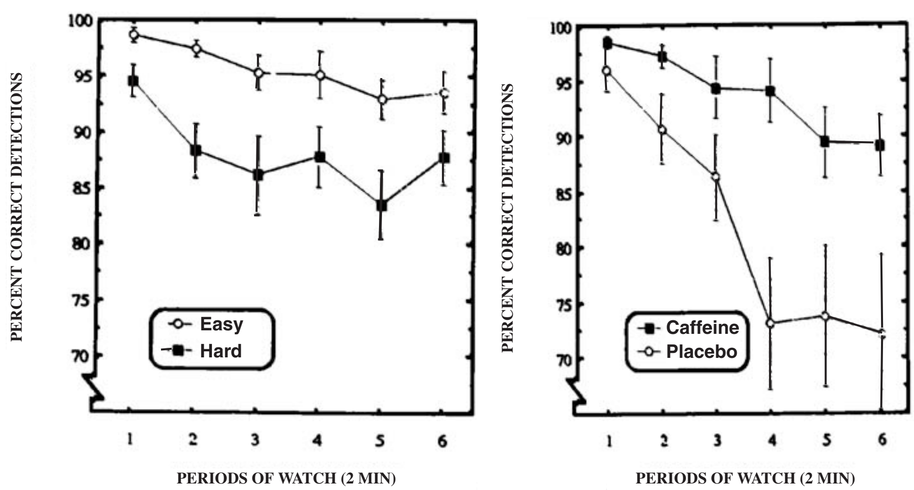


FIGURE 20 Mean percentages of correct detections over time in the abbreviated vigil. The left panel displays data for easy- and hard-to-detect signals. The right panel displays data for observers who did or did not ingest caffeine prior to performing the vigil. Error bars are standard errors. After Temple et al. (2000).

Previous research with the NIRS technique shows that tissue oxygenation increases with the information processing demands of the task being performed by an observer (Punwani, Ordidge, Cooper, Amess, & Clemence, 1998; Toronov et al., 2001). Hence, one might expect that along with cerebral blood flow, cerebral oxygenation would also be related to vigilance performance. An advantage of the NIRS procedure is that it affords the opportunity to examine different brain regions, not just the left and right hemispheres as with TCD. In our investigation, recordings were secured from the frontal lobe because of PET and fMRI studies showing right dominance in this brain region during performance of a vigilance task (Parasuraman et al., 1998). In our study, resting cerebral oxygen saturation data were collected for 3 min prior to the experimental session to provide a baseline comparison.

Blood flow velocity and oxygenation were both found to be significantly higher in the right than in the left cerebral hemisphere among observers who performed the vigilance task. In contrast, hemispheric differences were not found with either measure among control observers who had no work imperative. The data for the blood flow measure are shown in Figure 21 and the comparable blood oxygenation results can be seen in Figure 22.

Clearly, the results of both experiments indicate that performance in the abbreviated vigil is right lateralized, a finding that coincides with the outcome of earlier blood flow velocity studies featuring more traditional long-duration vigils and with PET and psychophysical investigations. This parallel has several important implications. It provides strong support for the argument that the abbreviated vigil is a valid analog of long-duration vigilance tasks. The fact that the NIRS procedure yielded similar laterality effects as the TDC procedure further implies that laterality in vigilance is a generalized effect that appears in terms of both hemovelocity

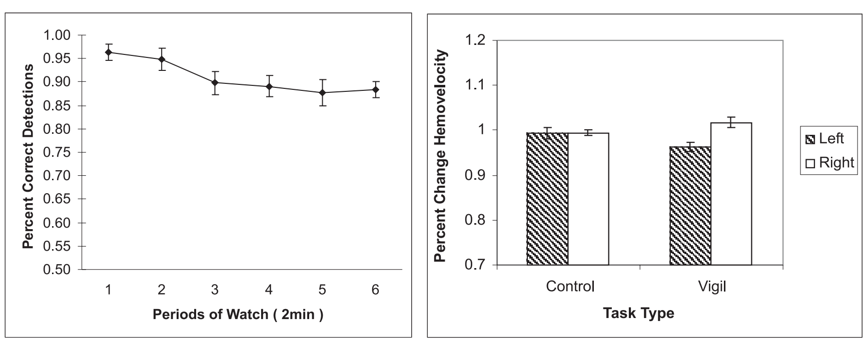


FIGURE 21 Performance over time (left panel) and left and right hemisphere hemovelocity scores (right panel) in the Helton et al. study (2007). Control = observers exposed to the display without a work imperative. Vigil = observers who performed the vigilance task.

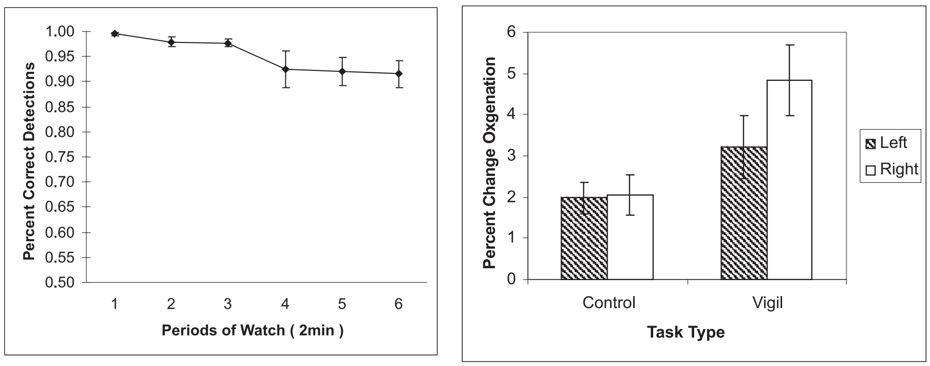


FIGURE 22 Performance over time (left panel) and left and right hemisphere blood oxygen saturation scores (right panel) in the Helton et al. (200&0 study. Control = observers exposed to the display without a work imperative. Vigil = observers who performed the vigilance task.

and blood oxygenation. It also implies that the NIRS procedure may be a useful supplement to the TCD approach in providing a noninvasive imaging measure of brain activity in the performance of a vigilance task.

Looking again at Figures 21 and 22, it is evident that a vigilance decrement was observed with the abbreviated task. However, declines in blood flow velocity or oxygenation did not accompany this performance effect—both indices remained stable over the course of the watch. It is possible that cerebral hemodynamics are structured so that overall hemispheric dominance emerges early in the time course of task performance but that temporally based declines in cerebral blood flow velocity and cerebral blood oxygen level require a considerable amount of time to become observable. Thus, the abbreviated 12-min vigil, which is only about 30% as long as the vigils employed in our earlier blood flow velocity studies, may not have been long enough to permit time-based declines in cerebral blood flow velocity of blood oxygen levels. We are currently exploring this possibility using the oxygen measure in a long-duration vigilance task featuring several levels of difficulty.

CONCLUSIONS

The experiments that we have described are part of an emerging effort in human factors developed by Parasuraman and Rizzo known as *neuroergonomics*, the study of the brain at work (Parasuraman, 2003; Parasuraman & Rizzo, 2007, Parasuraman & Wilson, 2008). One of the goals of neuroergonomics is to enhance understanding of aspects of human performance in complex systems with respect to the underlying brain mechanisms and to provide measurement tools to study these mechanisms. From this perspective, the use of TCD-based measures of cere-

bral blood flow to assess human vigilance can be considered a success. The vigilance studies have revealed a close coupling between vigilance performance and blood flow velocity and they provide empirical support for the notion that blood flow velocity may represent a metabolic index of information processing resource utilization during sustained attention. The demonstration of systematic modulation of blood flow velocity in the right cerebral hemisphere with time on task, memory load, signal salience and cueing, the sensory modality employed for signal detection, and target detection in the abbreviated vigil provides evidence for a right hemispheric brain system that is involved in the functional control of vigilance performance.

Another goal of neuroergonomics research is to use knowledge of brain function to enhance human–system performance. In additional to the theoretical and empirical contributions of TCD research, there are also some potentially important ergonomic ramifications. TCD may offer a noninvasive and inexpensive tool to monitor the monitor and to help decide when operator vigilance has reached a point where task aiding is necessary or operators need to be rested or removed.

In addition, a recently completed study in our lab (Reinerman et al., 2006) has shown that hemovelocity responses to a short high-information processing test battery, when coupled with a measure of task engagement provided by the Dundee Stress State Questionnaire (Matthews et al., 2002), predict subsequent vigilance performance. A multiple regression analysis showed that the multiple R using blood flow velocity and the subjective state measure as predictors was 0.36, a validity coefficient large enough to be practically useful (Warm, Matthews, & Finomore, 2007). The blood oxygenation measure that we have recently begun to employ may eventually provide similar information. Given the importance of vigilance in military, aerospace, industrial, and medical endeavors, such knowledge may contribute to enhancing productivity and improving public safety and health.

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designated by other documentation. In the conduct of research where humans are the subjects, the investigator(s) adhered to the policies regarding the protection of human subjects as prescribed by 45 CFR 46 and 32 CFR 219 (Protection of Human Subjects).

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